Army Research Laboratory

Simulation of Electromagnetic-Environment Susceptibility to Jamming Systems

by Berenice Verdin and Patrick Debroux

ARL-TR-7170 January 2015

NOTICES

Disclaimers

Army Research Laboratory
White Sands Missile Range, NM 88002-5513

ARL-TR-7170 **January 2015**

Simulation of Electromagnetic-Environment Susceptibility to Jamming Systems

Berenice Verdin and Patrick Debroux
Survivability/Lethality Analysis Directorate, ARL

REPORT DOCUMENTATION PAGE			*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED (From - To)**
January 2015	Final	2 September–2 November 2014

4. TITLE AND SUBTITLE Simulation of Electromagnetic-Environment Susceptibility to Jamming Systems	**5a. CONTRACT NUMBER**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) Berenice Verdin and Patrick Debroux	**5d. PROJECT NUMBER**
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) US Army Research Laboratory ATTN: RDRL-SLE-E White Sands Missile Range, NM 88002-5513	**8. PERFORMING ORGANIZATION REPORT NUMBER** ARL-TR-7170
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	**10. SPONSOR/MONITOR'S ACRONYM(S)**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The US military relies on communication devices to manage and control operations. It is important to find the susceptibility of friendly-force assets to insure command and communication in an often uncontrolled electromagnetic spectrum. Likewise, it is crucial to explore the enemy's susceptibility. Simulation of electromagnetic devices is often performed in a high-frequency structural simulator (HFSS). However, the complete susceptibility analysis cannot be performed in HFSS due to computational limitations including multiple devices. For this reason, this research project proposes to investigate the characterization of the susceptibility of radio frequency (RF) systems to jamming systems using HFSS (to obtain the far-field radiation patterns) and MATLAB software (to perform the susceptibility characterization). Thus, an algorithm that uses both reciprocity and superposition principles was developed. As a proof of concept a simulation was performed in HFSS where the RF system's and the jammer's far-field radiation patterns were simulated. The characterization of the susceptibility of RF systems was performed by obtaining 2-dimensional (2D) and 3-dimensional (3D) susceptibility areas.

15. SUBJECT TERMS

Susceptibility, jamming, radiation patterns, high-frequency structural simulator, HFSS

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Berenice Verdin
Unclassified	Unclassified	Unclassified	UU	18	**19b. TELEPHONE NUMBER** *(Include area code)* 575-678-5384

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Contents

List of Figures

1. Introduction

The susceptibility area of radio frequency (RF) systems is the area in which RF systems are more likely to be damaged or influenced by external electromagnetic energy. The susceptibility of an RF system depends on the characteristics of its receiver antenna and on the characteristics of the jammer's transmitter antenna.

Military organizations want to have control over the electromagnetic environment. Therefore, a characterization of the susceptibility of RF systems to jammer systems is required. The main limitation encountered in trying to determine the susceptibility of RF systems resides in the software used for electromagnetic simulation. A high-frequency structural simulator (HFSS) is used for the simulation of antennas and their characterization. The problem resides in simulating an electromagnetic environment that is composed of more than one antenna. For that reason, a new method to find the susceptibility of RF systems is proposed making use of reciprocity and superposition principles.

In order to perform the susceptibility characterization, the far-field radiation patterns of the 2 antennas are required. For this purpose, HFSS was used to simulate the radiation patterns of the 2 antennas taking into consideration that the RF system was inside a cavity. A dipole antenna inside a cavity was used to model a current induced on a coaxial cable. The cavity used approximates the dimensions of a land-mobile vehicle. The second antenna modeled was that of a jammer, the pyramidal horn antenna.

Once the radiation patterns were obtained the electromagnetic reciprocity principle was applied. The reciprocity principle states that a given antenna will have the same radiation pattern if the antenna is operating either in receiving mode or in transmitting mode.[1] After obtaining the radiation patterns the superposition principle is applied to obtain the susceptibility area of the RF systems. The method can be applied to 2-dimensional (2D) and 3-dimensional (3D) radiation patterns.

2. Antenna Design in HFSS

2.1 Characterization of the RF System's Antenna

The far-field radiation pattern of the receiver of the RF system is required to perform the characterization of its susceptibility. Consequently, a half-wave dipole was used as the receiving antenna of the RF system. This dipole is meant to model leakage through a coaxial cable. The half-wave dipole antenna was simulated using HFSS at a frequency of 1 GHz. The length of a half-wave dipole antenna should be equal to $\lambda/2$, where λ is the operating wavelength. Therefore,

for a frequency of 1 GHz the length used was 0.15 m. The half-wave dipole antenna was placed at the center of the Cartesian coordinate system as it is shown in Fig. 1.

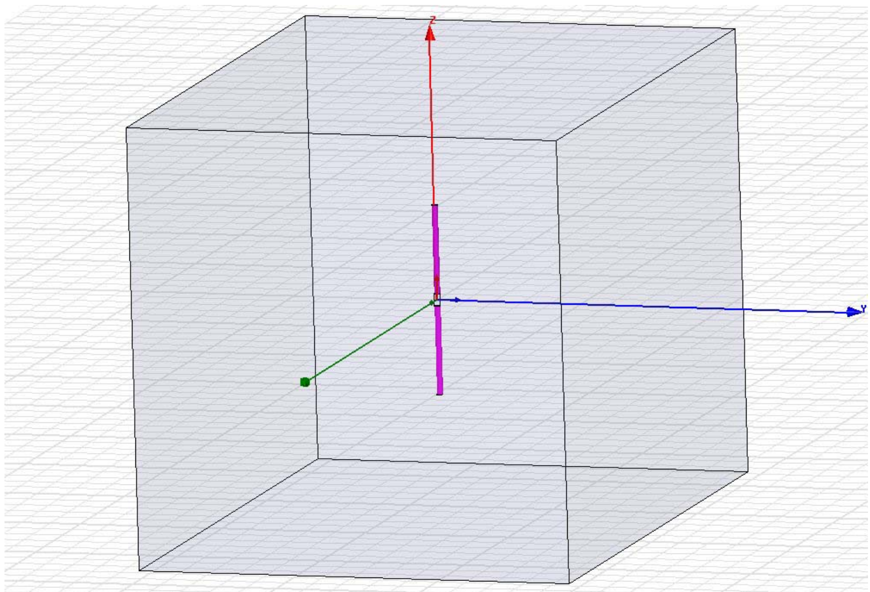

Fig. 1 Model of a half-wave dipole antenna at 1GHz in HFSS

The 3D far-field radiation pattern of the half-wave dipole antenna was simulated using HFSS. The radiation pattern is shown in Fig. 2.

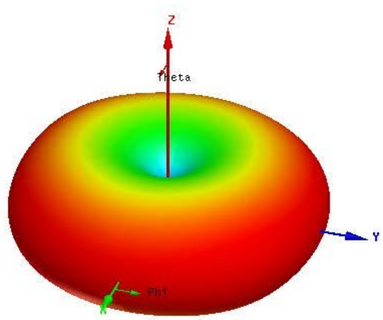

Fig. 2 The 3D radiation pattern of a half-wave dipole at 1GHz

The half-wave dipole antenna was placed inside a cavity with apertures. The cavity design has the form of a cube with four apertures that was used as a first approximation to a vehicle. The cavity was modeled of perfect electric conductor and glass (apertures). The cavity used is shown in Fig. 3.

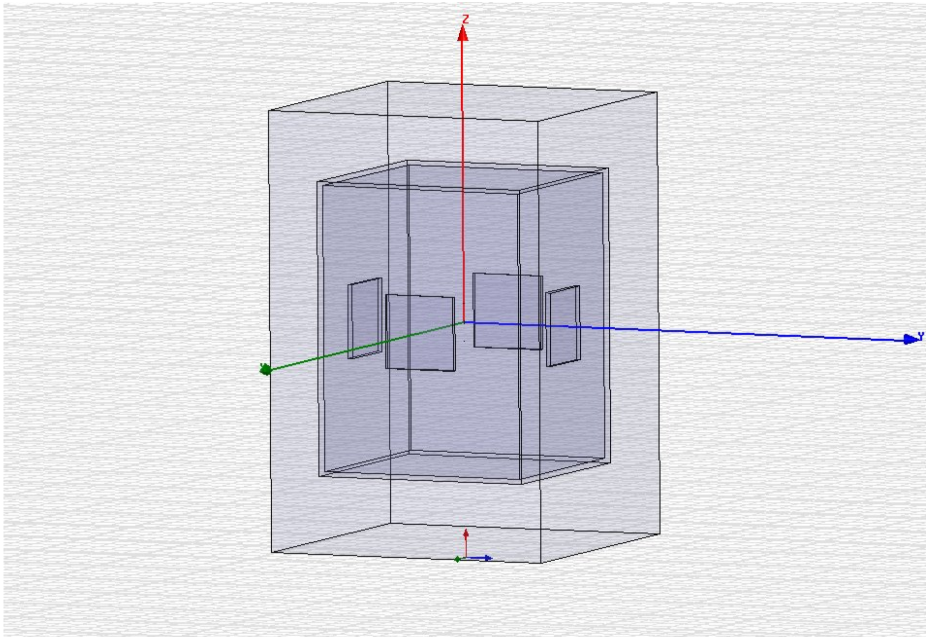

Fig. 3 Cavity with 4 apertures simulated in HFSS

The far-field radiation pattern of the half-wave dipole inside the cavity is shown in Fig. 4. As expected, the radiation pattern has 4 main lobes that coincide with the 4 apertures of the cavity.

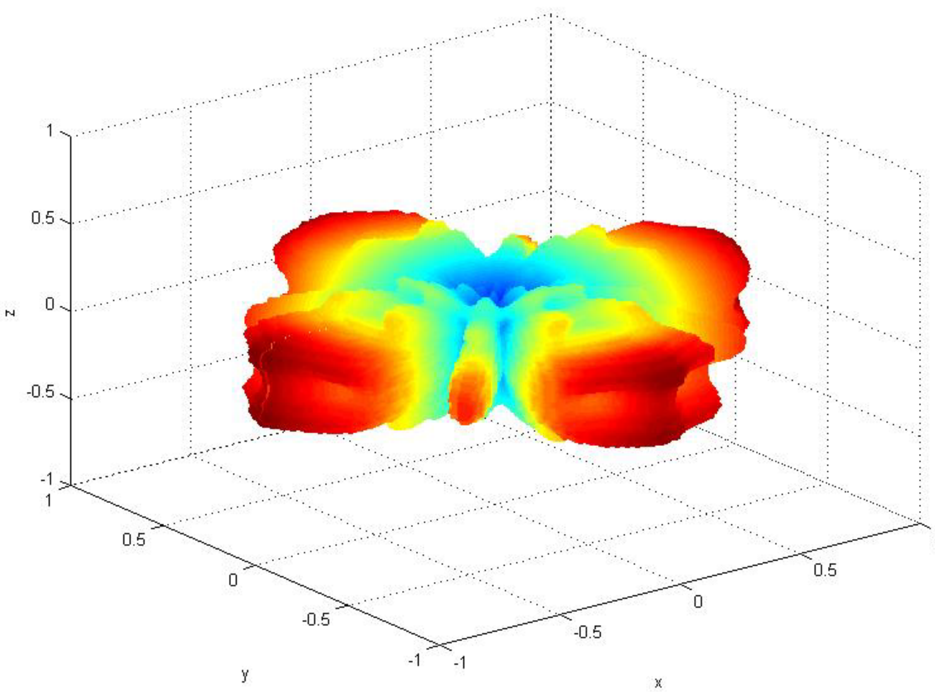

Fig. 4 Radiation pattern of the half-wave dipole inside the cavity

2.2 Characterization of the Jammer's Antenna

A cylindrical horn antenna was used to simulate the antenna of the jammer in transmitting mode. A 1-GHz cylindrical horn antenna was designed in HFSS. The model for the jammer antenna is shown in Fig. 5. The antenna aperture was placed at the origin of the Cartesian coordinate system with the aperture pointing into the z-axis.

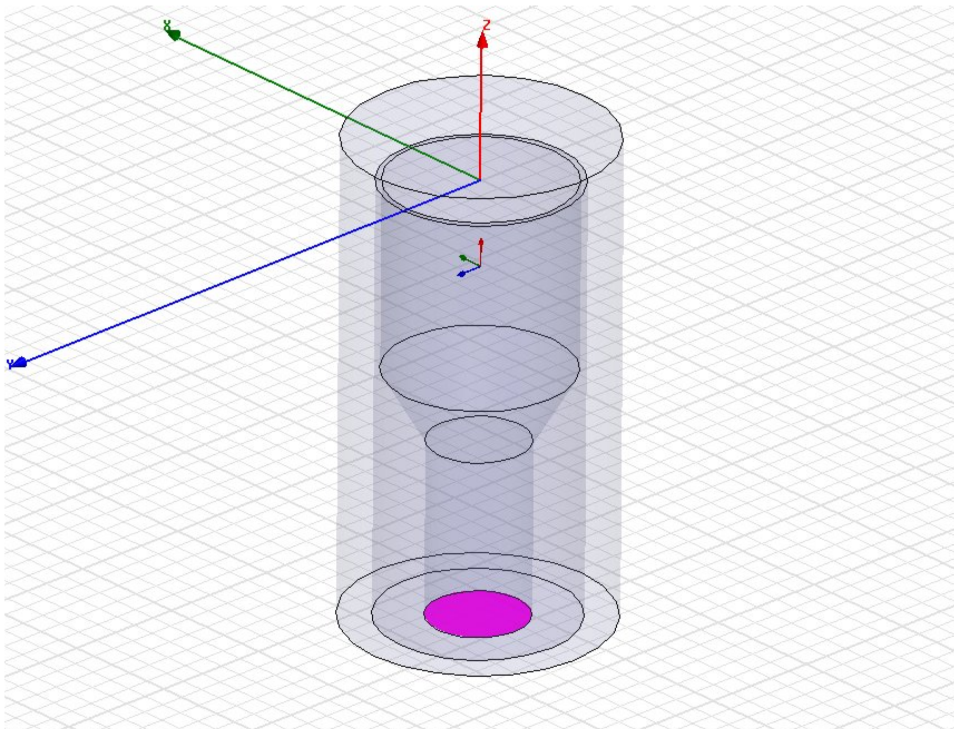

Fig. 5 Model of the horn antenna at 1 GHz designed in HFSS

The radiation pattern of the horn antenna is shown in Fig. 6. The radiation pattern has one main lobe pointing in the z-direction and small back lobes.

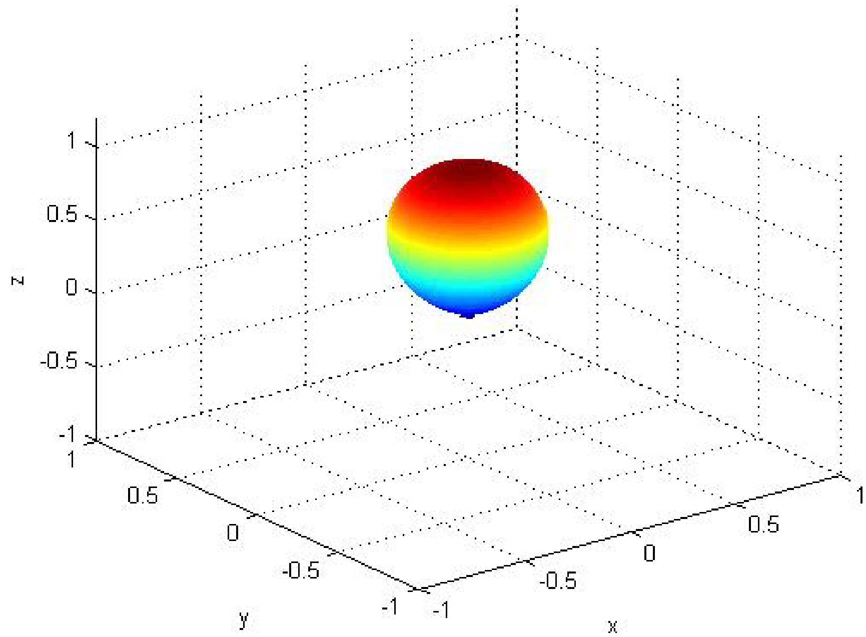

Fig. 6   Radiation pattern of the horn antenna at 1 GHz in HFSS

3. Numerical Simulation

3.1 Susceptibility Algorithm

The reciprocity and superposition principles used to perform the susceptibility analysis were applied in MATLAB. The text format files of the far-field radiation patterns of the jammer antenna and the RF system were exported to MATLAB. The files included the radiation pattern's information in spherical coordinates θ, φ, r. A coordinate-system transformation was performed. This routine was used to convert from spherical coordinates (θ, φ, r) to Cartesian coordinates (x,y,z). Eq. 1 was used for this purpose[2]:

$$\begin{gathered} x = r \sin\theta \cos\varphi \\ y = r \sin\theta \cos\varphi \\ z = r \cos\theta \end{gathered} \quad . \tag{1}$$

The rotation of the jammer antenna at different azimuth and elevation angles was performed to obtain the susceptibility of the RF systems to jammers at different relative locations. A rotation matrix was used to achieve the desired antenna orientation where the Euler angles ψ (azimuth angle) and β (elevation angle) were used to perform the rotation of the radiation pattern of the antenna. The rotation matrix $R_1(\psi)$ with respect to the azimuth angle is defined in Eq. 2. The angle ψ is measured in the x–y plane starting from the x-axis:

$$R_1(\psi) = \begin{bmatrix} cos\,\psi & 0 & -sin\,\psi \\ 0 & 1 & 0 \\ sin\,\psi & 0 & cos\,\psi \end{bmatrix} \quad . \tag{2}$$

The rotation matrix $R_2(\beta)$ with respect to the elevation angle β is defined in Eq. 3. The angle β is measured in the x–z plane starting from z-axis:

$$R_2(\beta) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\,\beta & sin\,\beta \\ 0 & -sin\,\beta & cos\,\beta \end{bmatrix} \quad . \tag{3}$$

The total rotation that incorporates both a rotation with respect to β and a rotation with respect to ψ is the multiplication of the 2 rotation matrices $R_T=R_1 \cdot R_2$. The radiation pattern in Cartesian coordinates was multiplied by the total rotation matrix R_T to achieve the desired rotation. For instance, Fig. 7 shows the jammer's radiation pattern for $\beta=\pi/2$ and $\psi=\pi/2$.

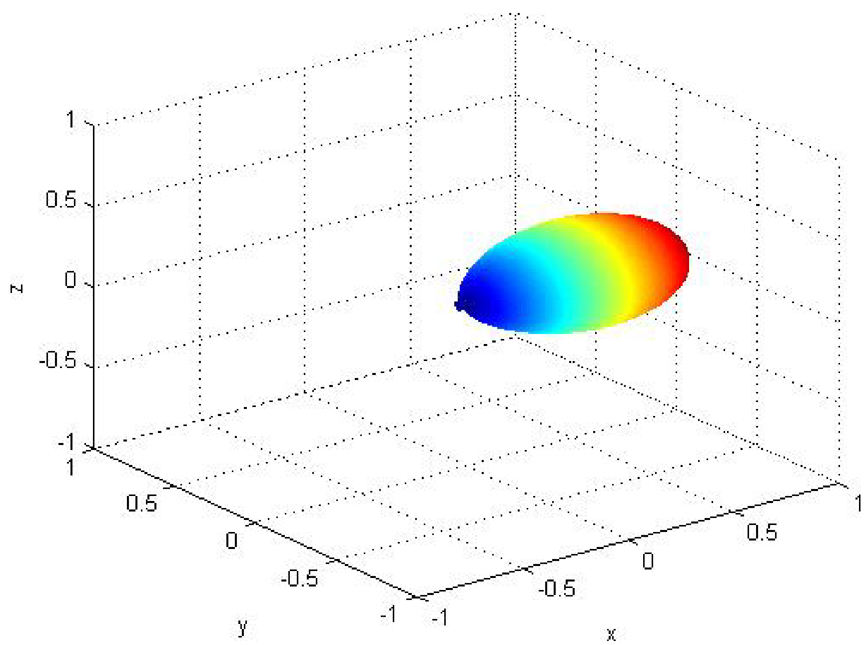

Fig. 7 Radiation pattern of the horn antenna including Euler angle rotations

In order to apply the superposition algorithm, the 2 radiation patterns need to have the same coordinate system. Therefore, the 2 radiation patterns were converted from a local spherical coordinate system to a global spherical coordinate system. A transformation from Cartesian coordinates to spherical coordinates is shown in Eq. 4:

$$\begin{aligned} r &= \sqrt{x^2+y^2+z^2} \\ \theta &= arctan\,\frac{\sqrt{x^2+y^2}}{z} \\ \varphi &= arctan\,\frac{y}{x} \end{aligned} \quad . \tag{4}$$

The superposition of the 2 radiation patterns was performed by using either the 2D or 3D data. The radiation patterns were superimposed as the point-by-point scalar multiplication of the 2 was performed. The process was repeated for every ψ that represents the field of view.

4. Susceptibility Analysis

The 3D susceptibility area of the RF system was obtained by using a susceptibility algorithm developed in MATLAB. The 2 radiation patterns where superimposed. Figure 8 shows the 3D susceptibility area when the horn antenna is at ψ=0 and β=π/2. A main lobe can be observed in this case that coincides with the aperture of the cavity. The susceptibility area also contains back lobes.

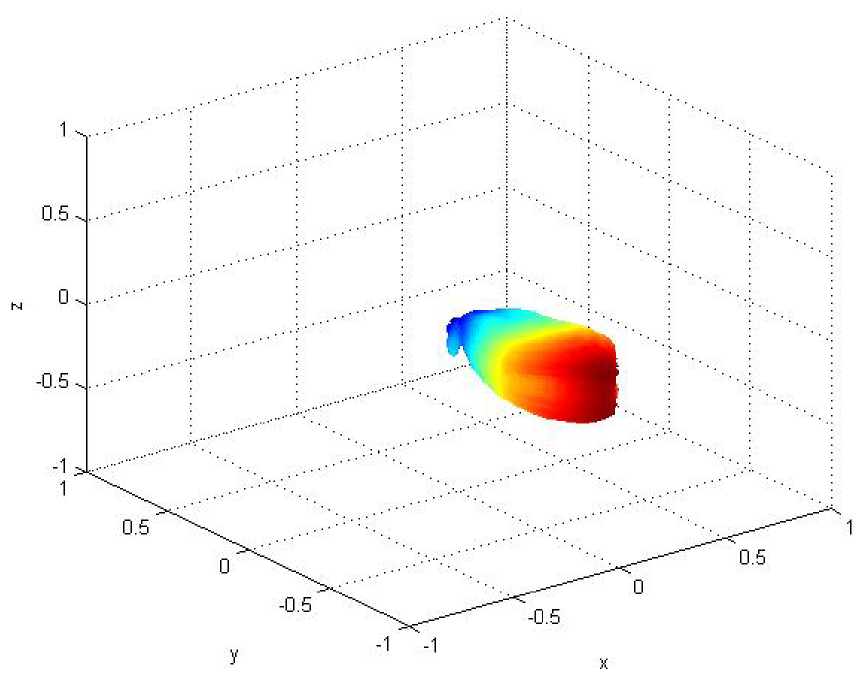

Fig. 8 The 3D susceptibility area

The 2D susceptibility area for β=π/2 and ψ=0 is shown in Fig. 9. The radiation pattern of the RF system (radiating from inside the cavity) and the jammer are also displayed in this figure.

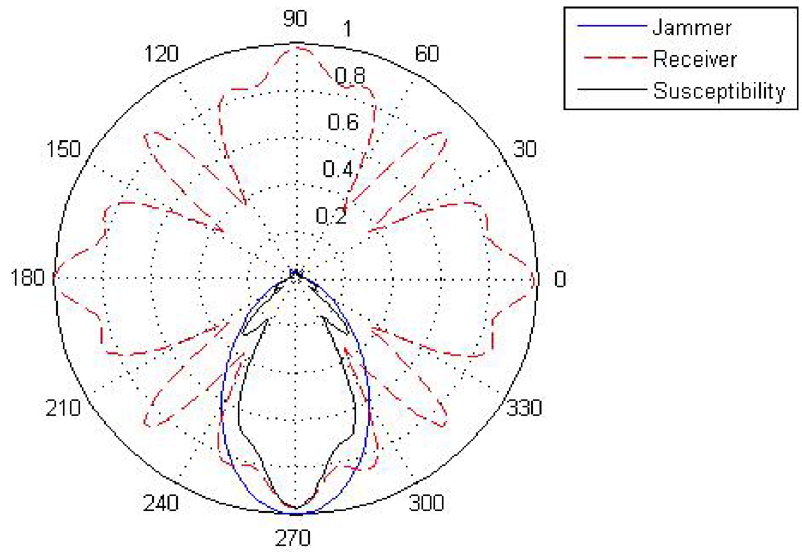

Fig. 9   The 2D susceptibility area

Another simulation was performed where the cavity with the dimensions of a land-mobile vehicle was designed in HFSS. The cavity used for simulations is shown in Fig. 10. The cavity has 6 apertures with larger apertures, modeling the windshield, at the front.

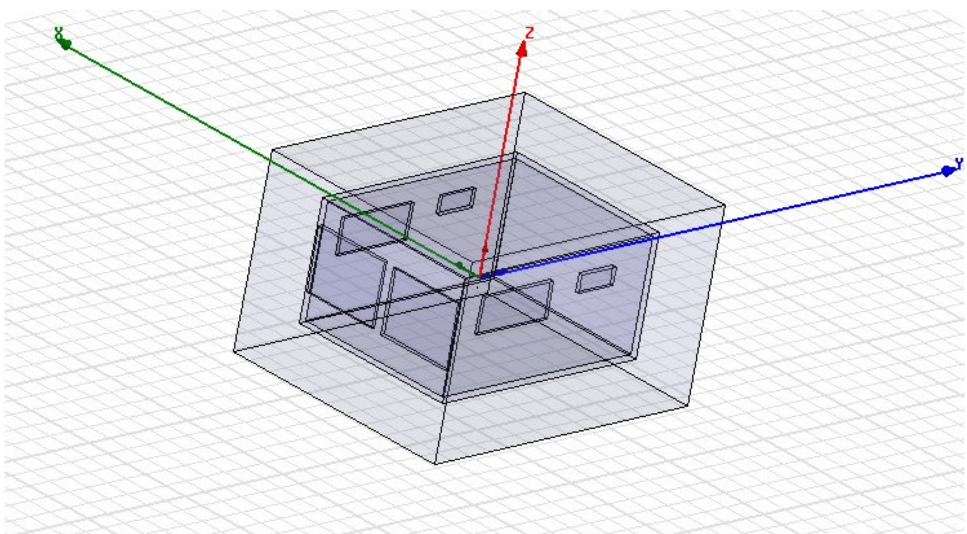

Fig. 10   Model of cavity with approximate land-mobile vehicle's dimensions

The radiation pattern of the half-wave dipole placed inside the cavity is shown in Fig. 11. It can be observed that the radiation pattern has 2 main lobes in the direction of the front apertures of the cavity.

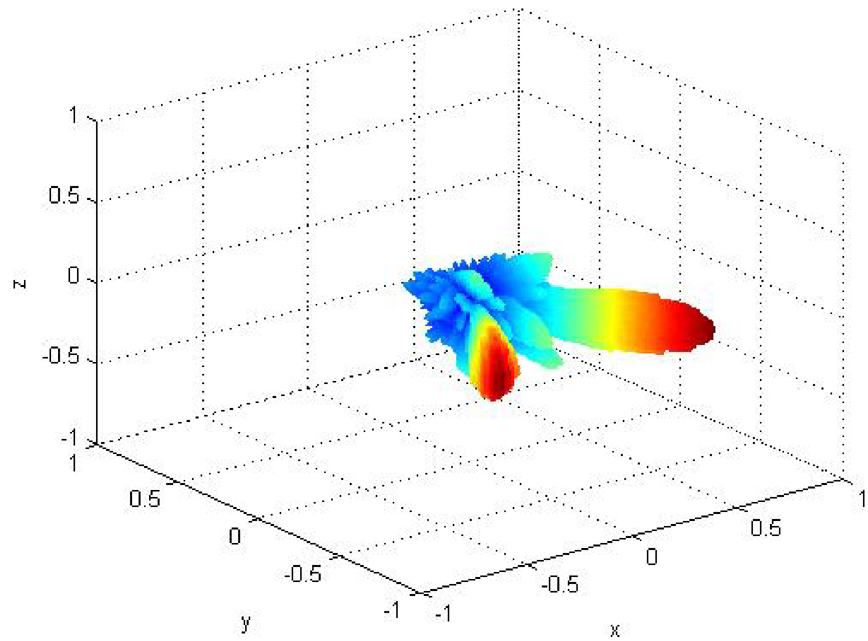

Fig. 11 Radiation pattern of the cavity with approximate land-mobile vehicle's dimensions

The susceptibility algorithm was applied and the 3D susceptibility area is shown in Fig. 12.

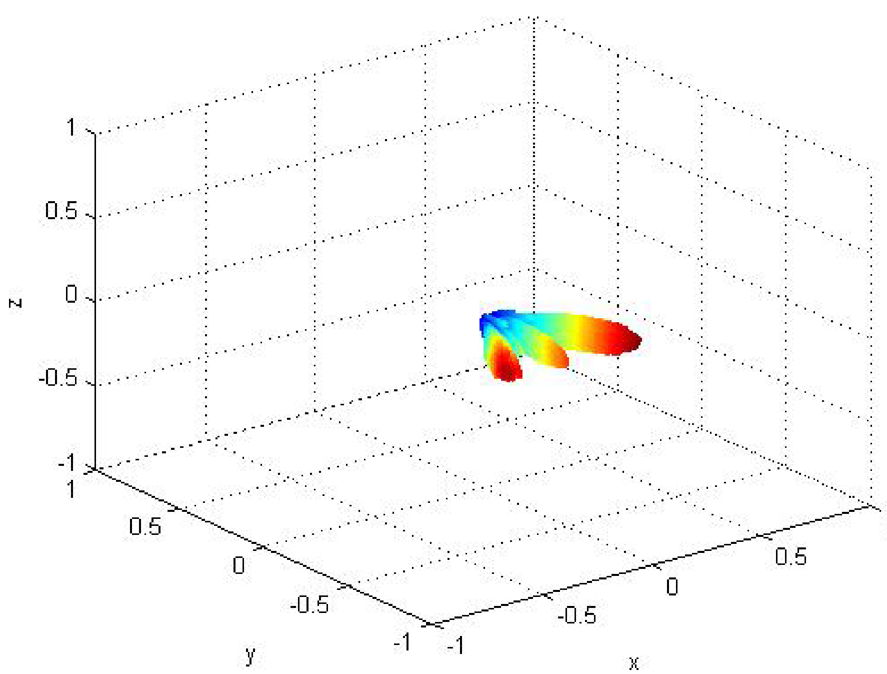

Fig. 12 The 3D susceptibility area

The 2D susceptibility can be observed in Fig. 13. The radiation pattern of the RF system (inside the land-mobile-vehicle cavity model) and the jammer are also displayed in the figure.

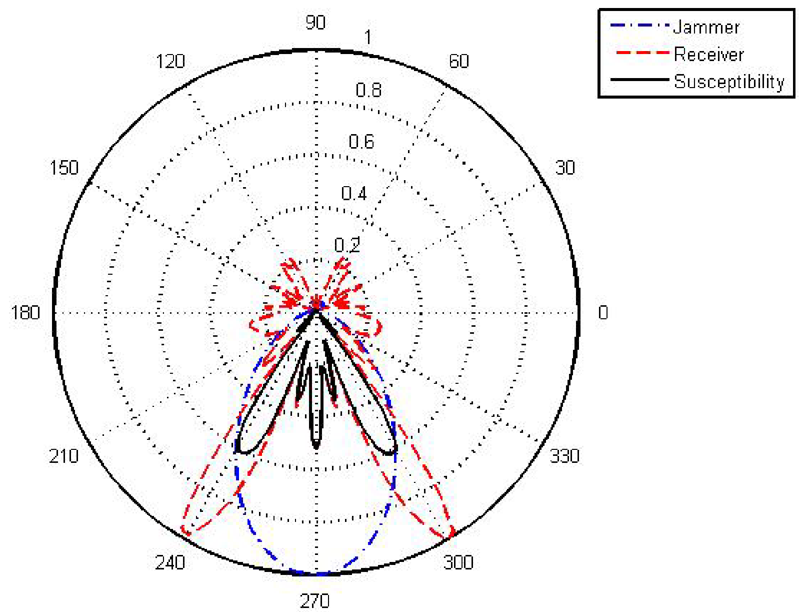

Fig. 13 The 2D susceptibility area

5. Conclusions

An algorithm that can be used to obtain the susceptibility area of RF systems was developed. The algorithm provides the 2D or 3D susceptibility area of RF systems. The susceptibility area depends on ψ (azimuth) and β (elevation) angles, given that the susceptibility area depends on the location of the jammer antenna. Therefore, the algorithm can take the location of the jammer antenna into consideration. The algorithm was evaluated using 2 cavities: one with 4 equal apertures and the other one that resembles a real land-mobile vehicle. For both cases, the 2D and 3D susceptibility area were obtained. The development of this algorithm overcomes the limitation of current electromagnetic-simulation software currently used.

6. References

1. Balanis CA. Antenna theory: Analysis and design, 2nd ed. John Wiley and Sons; 1997.
2. Sadiku M. Elements of electromagnetics, 5th ed. New York (NY): Oxford University Press Inc.; 2010.

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
2 (PDFS)	DIRECTOR US ARMY RESEARCH LAB RDRL CIO LL IMAL HRA MAIL & RECORDS MGMT
1 (PDF)	GOVT PRINTG OFC A MALHOTRA
1 (HC)	DIR US ARMY EVALUATION CTR HQ TEAE SV P A THOMPSON 2202 ABERDEEN BLVD 2ND FL APG MD 21005-5001
4 (2 HC 2 PDF)	DIR USARL RDRL SL J BEILFUSS (HC) P TANENBAUM (HC) RDRL SLE R FLORES
1 (PDF) 1 WORD VERSION	US ARMY RSRCH LAB MELE ASSOCIATES INC ATTN RDRL SLE E D NEVAREZ
4 (HC)	RDRL-SLE-E P DEBROUX